

Modeling Coastal Ocean Optical Properties for Coupled Circulation and Ecosystem Models

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LONG-TERM GOAL

The overall goal of this work, now completed, was to develop an extremely fast but accurate radiative transfer model, called EcoLight, for use in coupled physical-biological-optical ecosystem models, and then to demonstrate the ecological necessity and computational feasibility of including accurate light field predictions in coupled physical-biological-optical ecosystem models.

OBJECTIVES

Currently available ecosystem models often use fairly sophisticated treatments of the physics (e.g., advection and upper-ocean thermodynamics and mixing) and biology (e.g., primary production and grazing) but use grossly oversimplified treatments of the optics. The optics component of coupled ecosystem models is sometimes just a single equation parameterizing the scalar irradiance or photosynthetically available radiation (PAR) in terms of the chlorophyll concentration. Such simple models often fail even in Case 1 waters, and they can be wrong by orders of magnitude in Case 2 or optically shallow waters. The objective of this work was develop a radiative transfer model that can be used in coupled models to bring the optics component up to the level of accuracy and sophistication needed for ecosystem models that are being applied to any water body, including Case 2 and optically shallow waters.

APPROACH

The Hydrolight radiative transfer model (www.hydrolight.info) provides an accurate solution of the radiative transfer equation (RTE) for any water body, given the absorption and scattering properties of the water body and boundary conditions such as incident sky radiance and bottom reflectance. Unfortunately, the standard version of Hydrolight requires too much computer time to make it suitable for use in ecosystem models where the light field must be computed at many grid points and at time intervals of order one hour. However, ecosystem models require only the scalar irradiance as a function of depth and wavelength, $E_o(z, \lambda)$, which makes it possible to optimize the Hydrolight code to run extremely fast. In particular, because irradiances are computed as azimuthal integrals of the radiance, it is possible to solve the azimuthally integrated RTE to obtain azimuthally averaged radiances, from which the irradiances are easily obtained. Working with the azimuthally integrated RTE removes much of the computation load in Hydrolight, which solves for azimuthally dependent radiances. I therefore tailored the Hydrolight code to run as fast as possible with the constraint that the

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computed $E_o(z,\lambda)$ values at the bottom of the euphotic zone must be accurate to ten percent. The resulting highly optimized version of Hydrolight is called EcoLight.

WORK COMPLETED

The basic development of EcoLight was completed in the early stages of this contract as part of my work on the ONR Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE). This year's work merged EcoLight with the ROMS-EcoSim model (Bissett, *et al.*, 1999), which was used for ecosystem simulation in the HyCODE program. The EcoLight subroutine takes the component concentration profiles generated by EcoSim, converts the concentrations to absorption, scattering, and backscattering coefficients, generates scattering phase functions having the proper backscatter fraction, and uses those IOPs along with sky conditions and other input passed down from ROMS-EcoSim to compute the scalar irradiance as a function of depth and wavelength. EcoLight also computes the nadir-viewing remote-sensing reflectance R_{rs} , which is useful for comparison with hyperspectral imagery of the region being simulated. No other ecosystem light model can predict R_{rs} for prediction validation.

RESULTS

I compared EcoSim's biological predictions when using its original analytic irradiance model with its predictions when using EcoLight with various optimizations. The present simulation was for mid-latitude, open-ocean, Case 1 water. The clear-sky irradiance computations were driven the latitude, longitude, and time of day, and the computed clear-sky spectral irradiances were rescaled to match the measured wavelength-integrated values used by ROMS for its mixed-layer thermodynamics calculations. The model was run for 100 days, with output being saved at noon and midnight to show diurnal variability. The time step was 540 s, which was set by ROMS for computational stability. A 100 day simulation thus required 16,000 time steps. Irradiances were computed within EcoSim only when the sun was above the horizon.

In the first comparison, both the analytic and EcoLight EcoSim versions computed the irradiances *de novo* at every time step (notation: ETS) when the sun was above the horizon and at every grid point (EGP). EcoLight computed its irradiances at every wavelength (EW) used by EcoSim down to a depth z_o where the scalar irradiance decreased to $F_o = 0.001$ (the 0.1% light level) of the surface value. The exact irradiances were extrapolated down to 210 m, the maximum depth used by ROMS in this simulation, even though the values at great depths are not used by EcoSim. These EcoLight computations thus give highly accurate irradiances throughout the euphotic zone for the IOP and sky inputs passed to EcoLight by ROMS and EcoSim. This full EcoLight simulation is therefore taken to be the baseline for comparison with the analytic code and optimized EcoLight runs.

Figure 1 shows the time development of the total Chl_a (the sum of Chl_a for the four EcoSim phytoplankton functional groups) for the analytic (purple curve) vs. the full EcoLight version of EcoSim (blue curve) at a depth of 1.0 m. The first ~35 days are affected by initial numerical transients as the ecosystem comes into balance. Over days 50-100, the average Chl_a concentration at 1 m depth computed using the analytic irradiance model is 0.81 mg m^{-3} , vs. 0.51 mg m^{-3} when the irradiances are computed exactly by EcoLight. The respective differences are 0.67 vs 0.40 at 19.1 m depth, and 0.115 vs 0.124 at 38.5 m. The analytic-model Chl_a values are thus roughly 60% greater than the exact-model values within the surface mixed layer (down to about 20 m), where the different light calculations can be expected to make the most difference in the biology. At depth 38.5 m, which is near the bottom of the euphotic zone (if defined as the 1% PAR level, the bottom of the euphotic zone varies from 30 to

50 m in these simulations), the values are almost the same because there is very little primary production there. The Chl_a concentrations at great depth are affected only by settling from the upper ocean layers.

This comparison establishes the first important result of this study: *Accurately computed irradiances give significantly different ecosystem evolution within the euphotic zone compared to approximate, analytic irradiances.*

These preceding calculations required 115,946 computations of the irradiances (approximately 70 times per day for 100 days and 16 grid interior points of the 6x6 ROMS grid), each for 60 wavelengths and throughout the euphotic zone. The estimated run time for that many HydroLight runs to 50 m depth with an average $Chl_a = 0.7 \text{ mg m}^{-3}$ is 313 days (on a 2 GHz PC with 1 Gbyte of RAM). The corresponding EcoLight run took about 61 hours, which is a vast improvement over HydroLight but still impossibly long compared to the analytic-model run time of 17 minutes. The question then was how much more EcoLight could be speeded up.

It is not necessary to recompute the irradiances at every 540-second time step used by ROMS, nor is it likely that the irradiances must be computed independently at every spatial grid point in regions where a water body is almost laterally homogeneous. Similarly, it may be sufficient to compute the irradiances at fewer wavelengths, and then interpolate to obtain irradiances at the finer wavelength resolution needed by EcoSim. It may also be sufficient to solve the RTE only very near the sea surface, where optical boundary effects are important, and then to extrapolate the irradiances to deeper depths. I therefore investigated various options for calling EcoLight within EcoSim, which still updates the biology at every time step and every grid point throughout the euphotic zone.

I considered the following options. EcoLight can be called only once per hour (1HR). At time steps where EcoLight is not called, the most recently computed exact spectral irradiances are simply rescaled by the ratio of the current sky irradiance to that at the time of the previous full computation. This should give good irradiances if the IOPs have not changed greatly since the last full calculation. EcoLight can be called at one grid point (1GP), and the irradiances at that point can be rescaled in the same manner and applied at the nearby grid points. This should give reasonably good predictions if the IOPs are not greatly different between the grid points where the exact computation is made and where the rescaled irradiances are applied. EcoLight can solve the RTE exactly to a shallow depth corresponding, say, to $F_o = 0.1$ or 0.5 (the 10% or 50% light levels), and the irradiances at the corresponding z_o can be extrapolated to greater depths. This extrapolation will be accurate to the extent that the depth changes in the irradiances are proportional to the absorption coefficient and the mean cosine does not further change with depth. Finally, EcoLight can be called at only every second wavelength (E2W) after the first, and the intermediate wavelengths can be obtained by interpolation from the computed ones. These options can be applied in any combination.

Figure 1 also shows the results obtained when EcoLight was called with various combinations of the above options as shown in Table 1. Runs denoted “every hour” (1HR), for example, call EcoLight once per hour after the first call after sunrise. The “1 grid point” (1GP) runs call EcoLight only at one grid point of the ROMS grid and then uses those values at all other grid points. “Every 3rd wavelength” (E3W), for example, means that every third wavelength is solved after the first, i.e., wavelengths 1, 4, 7, 10,..., with values at wavelengths 2 and 3 being obtained by interpolation between the solutions for 1 and 4, etc.

Table 1. EcoLight options used in comparison runs. The depths in the F_0 column are the corresponding z_0 depths for PAR at day 60 of the simulations. (The corresponding depths for the analytic model are always less because the Chl_a values are greater in the mixed layer.) The run times are on a 2 GHz PC.

model	time resolution	grid resolution	F_0 (approx z_0)	wavelength resolution	run time hr:min
Analytic	9 min (every ROMS time step)	every grid point	—	every wavelength	0:17
EcoLight	9 min	every grid point	0.001 (70 m)	every wavelength	61:23
EcoLight	every hour	every grid point	0.01 (40 m)	every wavelength	7:32
EcoLight	every 2 hours	every grid point	0.1 (15 m)	every wavelength	2:52
EcoLight	every hour	1 grid point	0.5 (4 m)	every 2 nd wavelength	0:24
EcoLight	every 4 hours	1 grid point	0.5	every 3 rd wavelength	0:21

Figure 1 shows that the full EcoLight and the various EcoLight optimizations all give close to the same ecosystem predictions within the mixed layer, after a period (~35 days) of initial numerical transients. Figure 2 shows that below the euphotic zone (i.e, below about 40 m) the models all give similar results, although differences may develop later on as the different biology within the upper ocean begins to settle into the deeper water column. In the present simulation, the $1/K_d$ penetration depth, which is the depth “seen” in ocean color remote sensing, is no more than 10 m at blue and green wavelengths. Thus all EcoLight optimizations give similar predictions within the upper water column, as relevant to remote sensing.

The fastest EcoLight optimizations are more than two orders of magnitude faster than the full EcoLight (ETS, EGP, EW), and over 20,000 times faster than HydroLight. Indeed, these optimizations require only slightly more run time than the analytic version. It should be remembered that these run times shown in Table 1 include the ROMS physical and EcoSim biological calculations, as well as the optical calculations. In the analytical code, almost none of the EcoSim biological module time is required for evaluation of its analytic irradiance equations. Thus the increase in run time when a highly optimized version of EcoLight is used is only a few minutes in addition to the 17 min required for the physical and biological calculations in the present simulation. *This marginal increase in computational cost is a small price to pay in return for obtaining accurate irradiances and consequently improved ecosystem predictions.* Indeed, for the present idealized ecosystem at least, it is possible to solve the RTE only for the upper few meters of the water column, once every hour or so, and at less wavelength resolution than required by EcoSim, and still obtain almost the same results as for the full EcoLight calculation at every time step, grid point, and wavelength to great depth.

This comparison establishes the second important result of this study: *Sufficiently accurate irradiances can be obtained within the mixed layer by numerically solving the RTE with little more run time than is required for analytic irradiances.*

A draft paper has been prepared on these results. Its submission is awaiting the results from a set of five-year simulations, which will replace the 100-day simulations shown here.

IMPACT/APPLICATION

Predictive ecosystem models are playing an increasingly important role in our understanding of the oceans. Applications of such models range from predictions of water clarity for military purposes to management of coastal waters for fisheries. The incorporation of the EcoLight model developed here into coupled ecosystem models will give improved accuracy in the predictions of primary production and related quantities made by such models. As the coupled models become more trustworthy in their predictions, they will become even more valuable as tools for ocean science.

TRANSITIONS

All versions of the EcoLight code have been delivered to Dr. Paul Bissett of the Florida Environmental Research Institute, who is using the code for various ecosystem studies. A version of the EcoLight code will be bundled in the next version of HydroLight, which is now under development.

RELATED PROJECTS

Dr. Paul Bissett of FERI has a postdoctoral student, Dr. Bronwyn Cahill at Rutgers University, who is continuing this work and performing multi-year ecosystem simulations. That work is supported by an NSF grant to Bissett.

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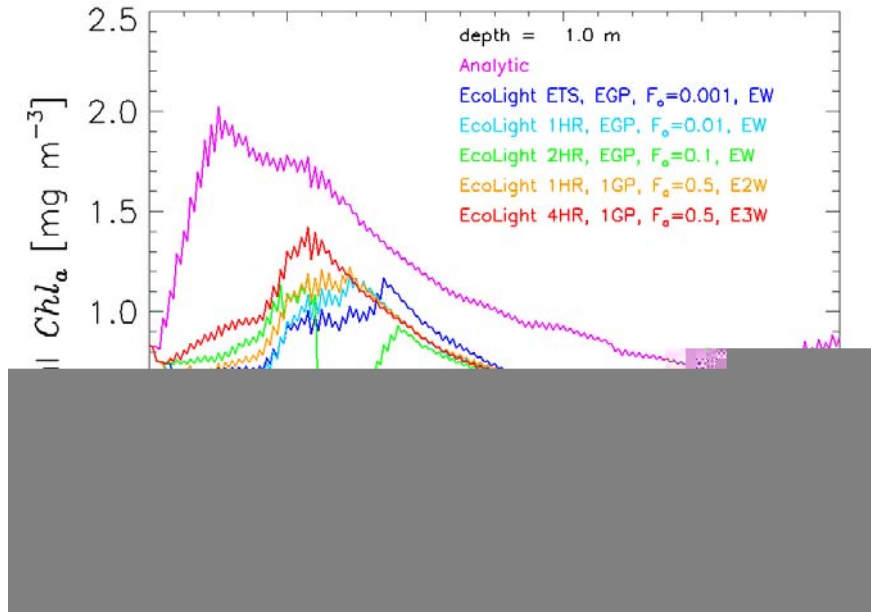


Fig. 1. Total chlorophyll a concentrations at depth of 1.0 m for the various simulations defined in Table 1. Note that the predictions made when using various version of EcoLight all settle down to a similar value, which is as much as a factor of two different from the value predicted when using the approximate, analytical light model. [The figure color codes the plotted chlorophyll a time series. The EcoLight-predicted values are always less than the values predicted by the default EcoSim light model.]

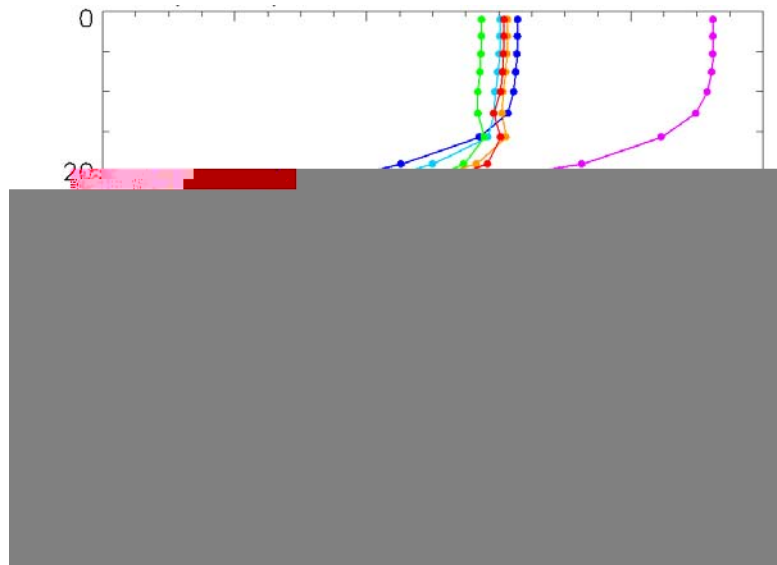


Fig. 2. Chlorophyll depth profiles corresponding to Fig. 1 at local noon of simulation day 60. The dots show the depths of the ROMS grid cell midpoints. . [The figure color codes the plotted chlorophyll a time series. Within the euphotic zone, the EcoLight-predicted values are always less than the values predicted by the default EcoSim light model.]